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EQUIVALENT INPUT NOISE MEASUREMENT AND ITS ASSOCIATED MEASUREMENT UNCERTAINTIES FOR MEMS MICROPHONES

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Abstract – Micro-electro-mechanical-system (MEMS) based microphones have grown remarkably in recent years. Their performance has been improving and approaching laboratory standard microphones. One of the challenges that MEMS microphones are facing is to achieve high sensitivity combined with low equivalent input noise (EIN). EIN in dB(A) indicates the lowest A-weighted acoustic pressure level that a microphone can detect relative to 20 μPa under atmospheric pressure. This paper discusses the measurement method, its setup and the associated measurement uncertainty for the EIN of MEMS microphones. The measurement method has been validated that it can reproduce the EIN at $13.61\ \mathrm{dB(A)} \pm 0.88\ \mathrm{dB}$ for a LS2F reference microphone, whose EIN is specified at 14 dB(A) in its manufacturer’s data sheet. The measurement setup can potentially measure EIN near 0 dB(A) provided that a good anechoic environment can be achieved. The MEMS microphone under test is able to deliver EIN at $43.61\ \mathrm{dB(A)} \pm 1.08\ \mathrm{dB}$.

Keywords: MEMS microphone, Equivalent Input Noise, measurement uncertainty, noise

1. INTRODUCTION

For micro-electro-mechanical-system (MEMS) based microphones, equivalent input noise (EIN) is the A-weighted equivalent input acoustic noise converted from the electrical noise measured at the output of the MEMS microphones in an anechoic environment under atmospheric pressure [1]. EIN demonstrates the lowest acoustic pressure level that a MEMS microphone can ever detect. Although sized in a few millimetres only, MEMS microphones have their pre-amplifiers packaged together in the form of an application-specific integrated circuit (ASIC). Constraint by their tiny size, it is very challenging for MEMS microphones to provide high sensitivity and yet low EIN. With technology advancement, it becomes possible.

The work in [2] has demonstrated that low noise floor in MEMS microphones is possible to achieve with design improvement. It also investigated various noise contributing sources in miniature microphones designed for hearing aids. The work in [3] provides a solid understanding on mechanical-thermal noise spectrum in a MEMS. This paper is more on the proper quantification of EIN where the noise is treated as a whole without differentiating the various contributing sources.

To quantify the EIN properly, both the sensitivity of the MEMS microphone and its overall electrical noise floor at the output needs to be measured accurately. The microphone’s sensitivity is needed to convert the electrical noise measured at the output to its equivalent A-weighted input acoustic noise. For both the sensitivity and electrical noise floor, it was measured under free field condition in an anechoic environment. The sensitivity of the MEMS microphone was determined using comparison method. The MEMS microphone was mounted side by side with a reference LS2F microphone and both of them measured the same acoustic source simultaneously at 90° incident angle.

For the electrical noise floor measurement, a low-noise real time spectrum analyser was used for the electrical noise measurement and subsequently the measurement raw data was processed to compute the EIN with acoustic A-weighting. Unlike conventional condenser microphones, the pre-amplifier of the MEMS microphone is not able to provide very high gain values. That results in rather low voltage to be measured at the MEMS microphone output. However, in our measurement setup no additional amplifier was connected to the MEMS microphone. Instead, a low-noise spectrum analyser was used to avoid additional noise and measurement uncertainty contribution.

In the corresponding sections of the paper, it will be discussed in detail the measurement setup and its associated measurement uncertainty for the EIN measurement of MEMS microphones. Following that, measurement results will be presented and discussed for a MEMS microphone. Conclusions will be given at the end of the paper.

2. MEASUREMENT METHOD & SETUP

2.1. Measurement Method

A low-noise spectrum analyser is used to perform the electrical noise spectrum measurement of the MEMS microphone. During measurement, the MEMS microphone is powered with DC bias and placed inside an anechoic box to isolate ambient noise.

After the electrical noise spectrum is measured, the measurement raw data is then processed using computational tools to add the acoustic A-weighting factors $R_a(f)$ according to [4] to the noise magnitude spectrum. $R_a(f)$ defined in (1) introduces a 2.0 dB loss at 1 kHz. As acoustic weighting is usually a normalised quantity respective to 1 kHz, this 2.0 dB loss is added to $R_a(f)$ for compensation [4].

$$R_a(f) = \frac{12200^2 f^4}{(f^2+20.6^2)(f^2+12200^2)\sqrt{f^2+107.7^2}\sqrt{f^2+737.9^2}} \quad (1)$$

The A-weighted noise spectrum is then converted to time domain A-weighted noise level n_A in Vrms as shown in (2), based on Parseval's theorem [5] on sampling and Discrete Fourier Transform (DFT) as shown in (3).

$$n_A = \sqrt{E_x / N} \quad (2)$$

$$E_x = \sum_{n=0}^{N-1} |x[n]|^2 = \frac{1}{N} \sum_{\gamma=0}^{N-1} |X[\gamma]|^2 \quad (3)$$

where $x[n]$ represents the A-weighted time domain discrete samples and $X[\gamma]$ is the A-weighted DFT pair, both of length N. E_x is the energy of $x[n]$.

At last, the EIN in Pa is obtained by dividing the time-domain electrical noise level n_A with $S_{MEMS,1kHz}$, the MEMS microphone's sensitivity in V/Pa at 1 kHz [1], as shown in (4). EIN in dB(A) relative to 20 µPa can then be derived easily as $20\log(EIN \times 10^6/20)$.

$$EIN = n_A / S_{MEMS,1kHz} \quad (4)$$

2.2. Measurement Setup

To measure the EIN, the MEMS microphone under test was placed in a specially designed testing jig made of Teflon as shown in Fig. 1 to facilitate electrical connections.

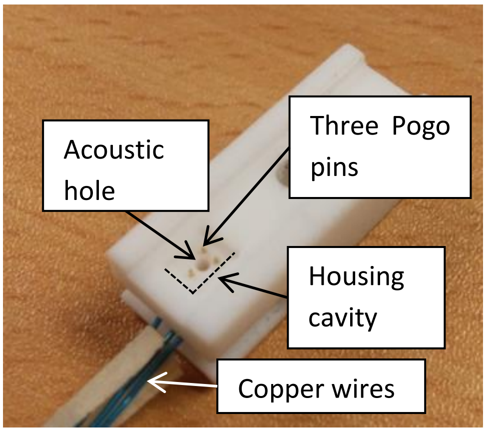

Fig. 1. Testing jib for MEMS microphones.

The MEMS microphone together with the jig was then placed in an anechoic box as shown in Fig. 2 to isolate ambient noise during measurement. The MEMS microphone's DC bias source and measurement connector was placed outside the anechoic box through wires on the testing jig and a side foam-sealed opening on the anechoic box.

The EIN measurement was performed using the following instrument listed in Table 1, and some BNC connectors and low noise cables:

Table 1. EIN measurement instrument.

No	Instrument Name
1	Real-Time Spectrum Analyser
2	Anechoic Test Box

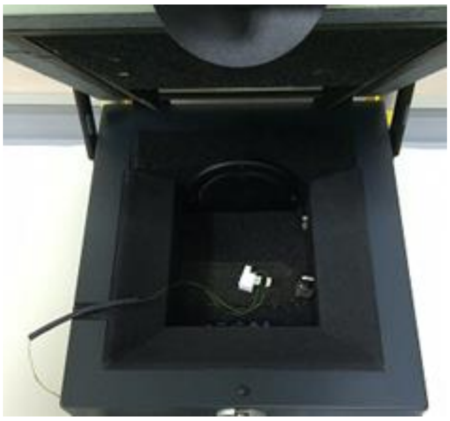

Fig. 2. MEMS microphone placed inside an anechoic box for ambient noise isolation.

The real-time spectrum analyser used for this noise measurement has a low noise floor itself of about 130 dBm at frequencies above 100 Hz by observation. In contrast, the electrical noise floor of the MEMS microphone under test is approximately 110 dBm by observation, which is 100 times higher than the measuring instrument. Thus the real-time spectrum analyser is adequate for the MEMS noise test.

To further reduce the intrinsic noise floor in the EIN measurement setup, a battery is used to provide DC bias to the MEMS microphone, instead of a DC power source. A DC power source can contribute additional noise as large as 15 dB to the whole noise spectrum.

To understand the measurement setup's overall noise testing capabilities, its own noise spectrum was captured and converted to EIN, which is around -5.26 dB(A) based on the sensitivity of MEMS microphone under test. Provided that a good anechoic environment can be achieved, the measurement setup is capable of supporting microphone noise measurement even below 0 dB(A), not only for MEMS microphones.

To validate our EIN measurement method and computational model, a standard microphone's noise floor was tested. From its specification datasheet, the EIN is at 14 dB(A). Using our measurement method and computational model, the EIN was measured at 13.61 dB(A) which is very close to the manufacture's data.

3. ASSOCIATED MEASUREMENT UNCERTAINTY

The major contributing factors to the MEMS EIN measurement uncertainty are i) the standard uncertainty of MEMS microphone's sensitivity at 1 kHz, $u(S_{MEMS,1kHz})$, and ii) the standard uncertainty of A-weighted electrical noise, $u(n_A)$, as supported by (4). As the anechoic test box is able to perform EIN measurement at 13.61 dB(A) for the reference standard microphone, we assume that its isolation performance is good enough for MEMS microphones under test and not a significant contributing factor in this measurement setup.

3.1. MEMS Microphone's Sensitivity at 1 kHz

The MEMS microphone's sensitivity was calibrated in an anechoic box based on comparison method to a standard ½-inch free-field microphone, which is our reference in this calibration. The sound pressure level at 1 kHz was generated by the speaker inside the anechoic box and it was measured by the reference standard microphone. The output voltage from the MEMS microphone was measured using a signal analyser. The sensitivity in V/Pa was derived by dividing the voltage level by the sound pressure level and it can be expressed as

$$S_{MEMS,1kHz} = \frac{V_{MEMS}}{V_{Ref}} S_{ref,1kHz} \qquad (5),$$

where V_{MEMS} and V_{Ref} are the voltage output from the MEMS microphone and the reference standard microphone, respectively and $S_{ref,1kHz}$ is the sensitivity in V/Pa of the reference standard microphone at 1 kHz.

Based on [6], the combined standard uncertainty $u(S_{MEMS,1kHz})$ of $S_{MEMS,1kHz}$ is estimated based on (6) at 0.31 dB, including reference microphone calibration $u(S_{ref})$ at 0.05 dB, voltage measurement done by the signal analyser $u(V)$ at 0.01 dB, difference in sound levels at two microphones due to difference in distance to the sound source $u(P_{diff})$ at 0.29 dB and repeatability u_{rep} at 0.05 dB.

$$u(S_{MEMS,1kHz}) = \sqrt{u^2(S_{ref}) + u^2(V) + u^2(P_{diff}) + u_{rep}^2} \qquad (6)$$

3.2. Acoustic A-weighted Electrical Noise

The electrical noise is measured using a real-time spectrum analyser. From the manufacturer's specifications, its frequency-domain measurement standard uncertainty at any given frequency u_{FFT} in dB can be estimated based on Root Sum of the Squares (RSS) method as shown in Table 2:

Table 2. Real-Time Spectrum Analyzer Uncertainty Budget.

Uncertainty Source	Probability Distribution	Standard Uncertainty in dB
Frequency Response	Rectangular	$0.3/\sqrt{3}$
Marker Readout Resolution	Rectangular	$0.01/\sqrt{3}$
Resolution Bandwidth Switching	Rectangular	$0.05/\sqrt{3}$
Relative Amplitude Accuracy	Rectangular	$0.7/\sqrt{3}$
Combined Standard Uncertainty u_{FFT} (based on RSS method)		0.44

$u(X[\gamma])$ in dB, the standard uncertainty of acoustic A-weighted noise spectrum, will have the same value of u_{FFT} in dB, as dB is a ratio/percentage uncertainty and weighting factors do not change the ratio. Thus the standard uncertainty of n_A, $u(n_A) = N u_{FFT}/N = u_{FFT}$.

3.3. Combined Standard Uncertainty

The combined type B standard uncertainty for the measurement of EIN can be evaluated as:

$$u_c(EIN) = \sqrt{u^2(S_{MEMS,1kHz}) + u^2(n_A)} \qquad (7).$$

With $u(S_{MEMS,1kHz}) = 0.31$ dB and $u(n_A) = 0.44$ dB, $u_c(EIN) = 0.54$ dB.

4. RESULTS & DISCUSSIONS

4.1. Measurement Method Validation

As discussed in Section 2.2, we have tested our measurement method on a reference standard microphone. On the microphone's data sheet, the EIN is stated at 14 dB(A) with no information on its associated measurement uncertainty. As it is a reference microphone, its calibration standard uncertainty at 1 kHz is $u(S_{MEMS,1kHz}) = 0.05$ dB and $u(n_A) = 0.44$ dB remains the same. Using our measurement method, an EIN of 13.61 dB(A) $\pm$ 0.88 dB has been obtained at a confidence level of approximately 95 % with a coverage factor $k = 2$, assuming Gaussian distribution. Assuming the microphone manufacturer has a similar measurement uncertainty, a measurement equivalence is achieved with $E_n = 0.24$.

4.2. EIN Measurement for a Sample MEMS Microphone

A sample MEMS microphone was tested using the EIN measurement setup and computational model. The system electrical noise floor was first measured with 100 times averaging as shown in Fig. 3 as a solid line. The system's EIN computed based on the MEMS microphone's sensitivity at 1 kHz (-37.17 dB relative to 1V/Pa) is -5.26 dB(A).

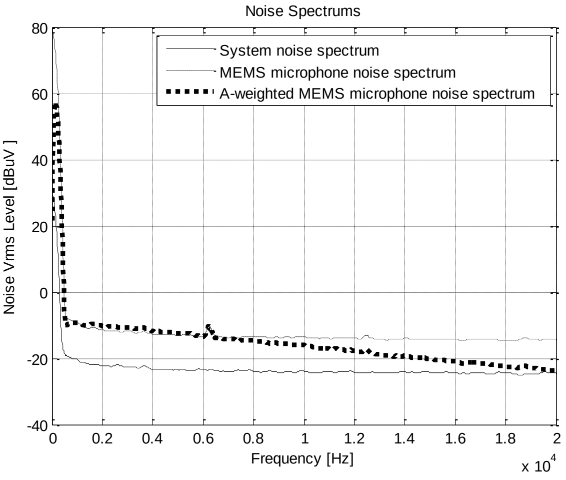

Fig. 3. Measured Noise Spectrums.

The MEMS microphone's electrical noise floor was then measured with 100 times averaging. Its noise spectrum is shown in Fig. 3 as a dashed line and its A-weighted noise spectrum is shown as a dotted line.

Five rounds of measurement were performed and the EIN was obtained at 43.65 dB(A), 43.56 dB(A), 43.57 dB(A), 43.61 dB(A) and 43.68 dB(A), respectively. The mean value is at 43.61 dB(A). The type A standard uncertainty of measurement is computed at 0.023 dB. The expanded measurement uncertainty considering type A, system type B $u_c(EIN)$, and the measurement resolution 0.01 dB for the EIN is evaluated to be equal to 1.08 dB, at a confidence level of approximately 95 % with a coverage factor $k = 2$, assuming Gaussian distribution.

In addition, 200 times averaging was also tried for the noise spectrum measurement. The EIN measured was at 43.68 dB(A), which has no observable improvement compared with EIN obtained under 100 times averaging. Thus we conclude that 100 times averaging is sufficient for EIN measurement.

5. CONCLUSIONS

In this paper, we have discussed the measurement method and setup to quantify the equivalent input noise (EIN) for MEMS microphones in National Metrology Centre. A low noise spectrum analyser together with an anechoic test box was used for the MEMS microphone's electrical noise measurement. A computational model has been established to convert the measured noise spectrum into time-domain EIN in Pa and thereafter in dB(A). The associated measurement uncertainty has also been evaluated.

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